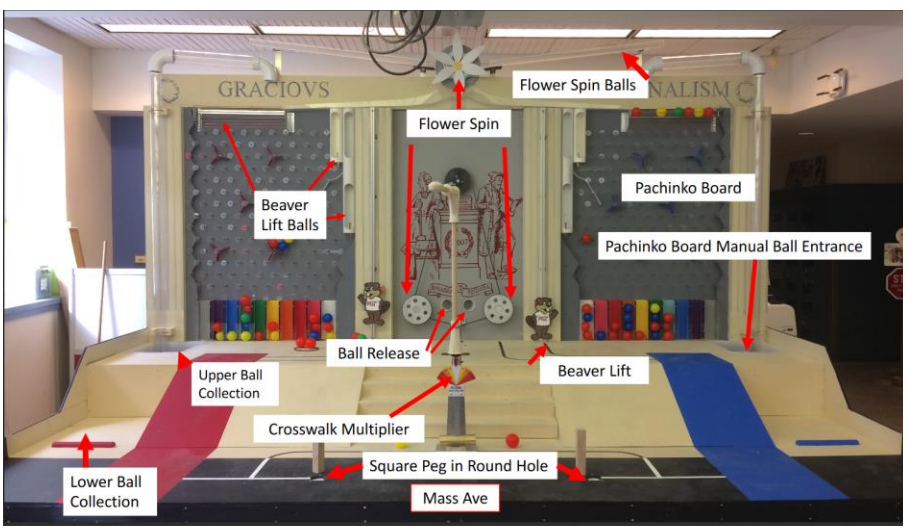
Background

Design & Manufacturing I (2.007) is an engineering robotics design class where students develop competence and self-confidence as engineers as they undergo a creative design process while applying physical laws. The culmination of the class is a final robot competition, where students compete against each other to see whose robot can earn the most points. The theme of this year's competition was 'Legacy.'

Each full round of play is two minutes long and comprises an initial 30-second autonomous period that automatically rolls into the 90-second "regular" remote-controlled period. Robots can earn points by the following methods:

- Dropping the square peg in the round hole: This move releases 18 balls into the game table, and the first robot to drop the peg into the hole earns additional points.
- Collecting balls: Points can be earned by placing them into designated bins in the game table.
- Lifting the beaver: Lifting the beaver earns points when it reaches certain heights in the column and releases balls into the Pachinko board.
- Spinning the beaver: Points are earned from the speed at which the disk is spun, and balls are also released into the Pachinko board.
- Pulling the multiplier: Pulling the multiplier earns a multiplier of points based on the angle it is pushed to.

There were also more specific and intricate rules, which I will address later, that influenced my design requirements.



Strategy

Drive main robot to flower spinner→Align spinner to wheel by spinning slowly until prongs are caught in the holes→Spin flower long enough to release all 14 balls→Drive robot to the front of ball-release hole→Autonomously drive 2nd robot to peg hole→Allow balls to shoot into robot, then drive to upper bin, and dump robot containing balls into upper bin

Points: $2.5^2 pts + 5 * [3pts, 6pts] + 9 * 4pts + 18 * 2pts = [93.25pts, 108.25pts]$

Ideation

I generated multiple strategies that explored the various actions my robot could take to earn points. With each strategy, I analyzed the range of points I could reasonably earn, estimated the time it would take to complete the actions, and approximations of how much power I would need from my motors to carry out the tasks. After that, I created a Pugh chart with the attributes Time Efficiency, Power Needed, Points, Risk, and Flexibility. Using the Pugh chart and gauging my personal interest, I decided to pursue spinning the flower and collecting balls afterwards. While lifting the beaver yielded the most points if lifted to the maximum height, I did not deem the risk of not reaching the maximum height worth giving up the flexibility of spinning the flower. Typical mechanisms for lifting the beaver take up more space than a typical spinning mechanism, thus spinning the flower still allowed me the space and resources to design the robot to also collect balls. Additionally, I considered the flower spinner as less risky because, even if I couldn't attain a maximum speed, I could a good amount of points from releasing the balls into the Pachinko board if I could spin the wheel long enough.

Design

Final Design Requirements:

- Achieve 0.4Nm torque to spin flower
- Minimize friction in spinner system
- Be within the $16in^3$ dimensional limit
- Be able to contain 18 balls

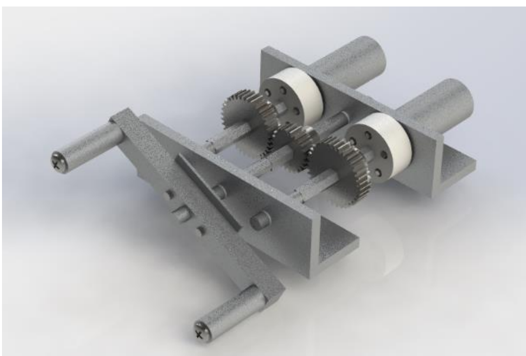
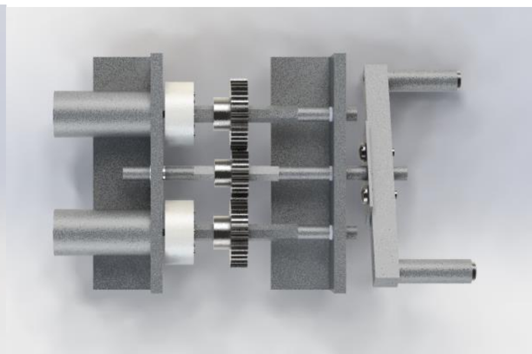
With the strategy decided, I then turned to generating conceptual ideas to carry out my strategy. I generated at least five concepts and decided to go with the concept pictured below with the presumptions that having one prong (which would fit into one of the small holes in the wheel) would be lightweight, and thus spin the wheel faster. I made a Delrin prototype of the concept and attached it to a hand drill to mimic being actuated by a motor. I realized that this prototype was very unstable, and if it were attached to a robot, the robot would tip from the reaction. Thus, I did some force-balance calculations (Appendix A) to analyze the force balance of the spinner and concluded that a symmetrical design would cancel out reaction forces, thus designed this second iteration (also pictured below). I once again attached it to a hand drill and noticed the better stability. I then connected it an LDO motor. I noticed that it could spin the wheel (only after it was only in motion) at a very slow speed. I also realized when the flower petal pushed a ball to the Pachinko Board, the ball creates an additional torque needed to spin the wheel. Thus, I measured a torque of 0.4Nm to be able to spin the wheel from rest.



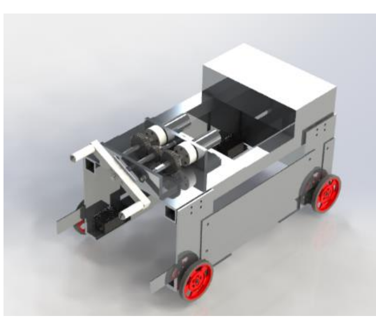
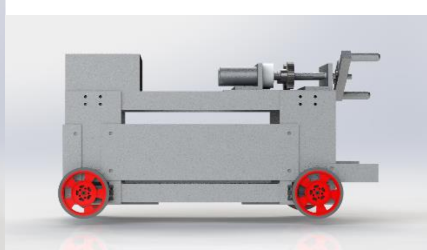
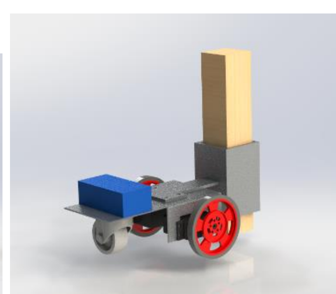
I had a limit of 2 LDO motors to use in my spinner system (the other 2 are for my peg-dropping secondary robot), and so I performed a calculation (Appendix B) to determine my gear ratio and to determine which LDO motor ratio to select, which ended up being a 3-gear-2-motor system with a 3:2 gear ratio and 57:1 LDO motors. With the power of two LDO motors, the goal of reaching 0.4Nm, and including an inefficiency constant of 0.5, my attained speed was 2.5 rad/s. Because of the low speed, I focused my attention on ensuring I can spin the wheel even with the added torque from the balls and spin the wheel long enough to release all 14 balls.

I designed the shaft of the spinner system to create minimal load on the bushings, which in turn would decrease the power lost due to friction on the bushings. I did this by making the distance between the two bushings large, while making the distance between the spinner and the closest bushing small. The analysis and calculation can be found in Appendix C.

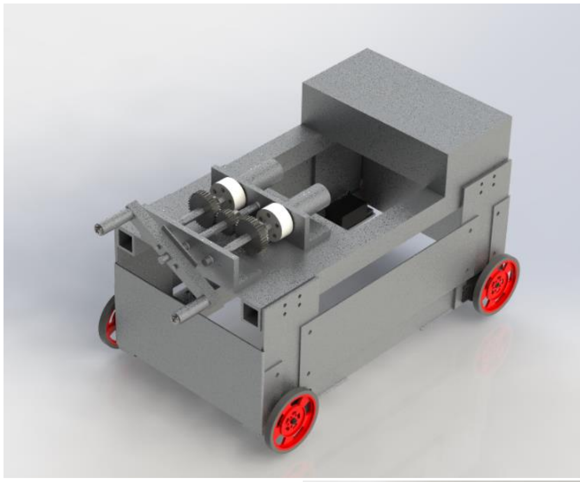
To further minimize friction in the spinner system, the made the diameter of the prong to be almost the diameter of the wheel's hole. If the diameter is too small, the prong would rattle in the hole more violently, and this would waste power. To mitigate wasted power, I made the prongs around 0.2in smaller than the whole so that the friction between them has a smaller magnitude, while the prong is still small enough to fit in the whole. Rudimentary illustration of this can be found in Appendix D.

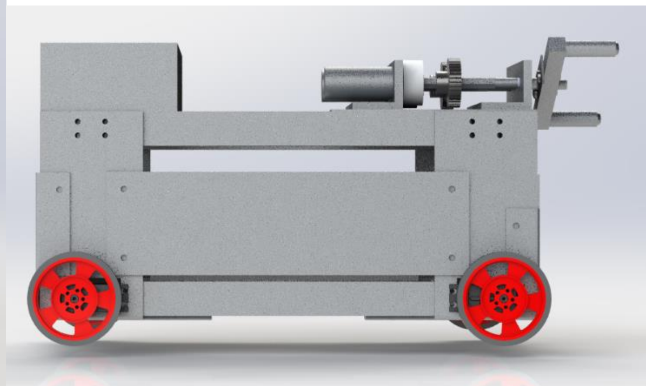



Because I am also collecting balls, I decided that the simplest way to pick up balls was to do so as they came out of the ball release and to be able to contain them as I drove to the upper bin. Therefore, I designed the frame of the robot to be hollow inside, allowing the balls to fill that empty space. The length and width were limited to 16in due to the game rules, and the spinner had to be 9in off the ground to be aligned with the wheel. I erected walls on the sides and back of the robot to prevent the balls from falling out when the robot was traveling, and the balls would shoot into the front of the robot from the shoot. And, I created a simple peg-dropping robot that will autonomously drive to the hole, with the peg being dragged along while being held in place, and the peg will simply fall into the hole.

Then, I realized that current design doesn't effectively prevent the balls from spilling out when traveling. Thus, I added a shield to the front, and the balls would thus enter the robot from the release through the top, which was still open, in-between the spinner in the front and counterweight at the back. If I were on campus, I would analyze the trajectory of the balls coming out of the shoot and determine the best position for the robot to be in to receive them. The analysis for the ball containment can be found in Appendix E.





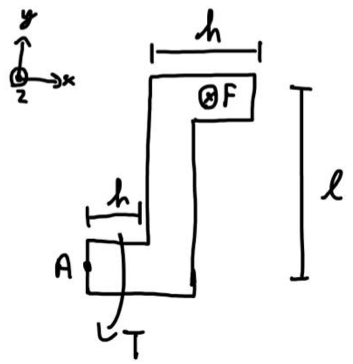
I chose the center of mass to be in the middle of the robot to make the driving experience easier, and I performed a sum of moment calculation (Appendix E) to see how the reaction torque from the wheel affected the robot.

<u>Experience</u>

Coming into 2.007, I had no previous exposure to robotics. My only experience designing and building something was with my 2.00b team the last year, and I had only once used a mill and lathe the summer before. Hence, when the class started, I was afraid. I overwhelmed seeing the previous years' robots, thinking about encountering the machine tools I didn't remember how to use, applying all the theoretical calculation I learned to something that practically needed to work. Yet, it was the same things I was afraid of that I also relished to encounter. Following a principled design process where I broke down my problems and milestones into smaller pieces, I was able to steadily make progress towards adequately creating designs and analyzing their features to optimize them. After being refreshed on and learning how to use new machine tools—I mainly used the bandsaw, drill press, lathe, mill, step shear, brooch tool, center punch, and more—I gained more confidence and competence machining, and also gained more confidence to ask questions and seek for assistance. Most of all, it was

fun. I felt on a roll when programming instructions into the milling machine. However, with campus closing and no longer able to build our robots, I was cut short while still fabricating my spinner system. While I lost the experience of fabricating a full-fledged robot, I still had a transformative experience designing and modeling a complete robot in SolidWorks, applying analytical calculations, and iterating when prototypes didn't work.

Appendix



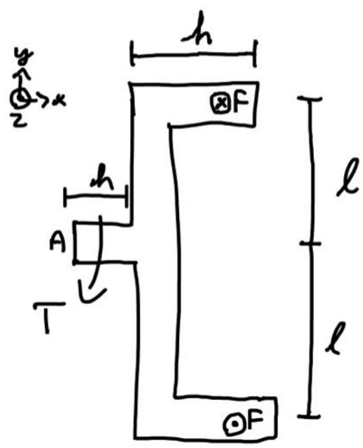
Appendix A

$$\Sigma M_A = T - F\ell - 2Fh$$

$$\Rightarrow T = F\ell + 2Fh$$

$$\Sigma F_z = F$$

↳ Creates a reaction force on bearing; Requires more force to remain stable



$$\Sigma M_A \doteq 0 = T - F\ell - 2Fh - F\ell + 2Fh$$

$$\Rightarrow T = 2F\ell$$

$$\Sigma F_z = F - F = \boxed{0}$$

∴ No reaction force from spinner on supporting bearing

∴ Symmetrical Design is better

Appendix B

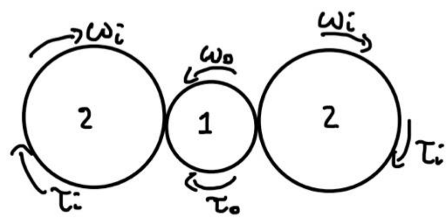
Goal: Achieve measured $\boxed{\tau = 0.4\,Nm}$ to spin flower and release ball.

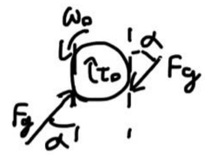
LDO Motor Power $\simeq 1W \Rightarrow 2$ motors $\rightarrow P = 2W$

$\therefore \omega_0 = p\,\frac{2}{0.4} = \boxed{2.5\,rad/s}$

0.5 to account for system innefiiciency

Gear Ratio:



① 

$\therefore \Sigma M = 0 = \tau_o - R_1 F_g \cos\alpha \Rightarrow \tau_o = 2R_1 F_g \cos\alpha$

② 

$\therefore \Sigma M = 0 = -\tau_i + R_2 F_g \cos\alpha \Rightarrow \tau_i = R_2 F_g \cos\alpha$

$\frac{24+24}{4} = 12$

$\therefore 2 = \frac{\tau_o}{\tau_i} = \frac{2R_1}{R_2} = 1.6$

$\frac{36+24}{4} = 15$

w/ Ratio: 3:2 $\Rightarrow$ 36t : 24t

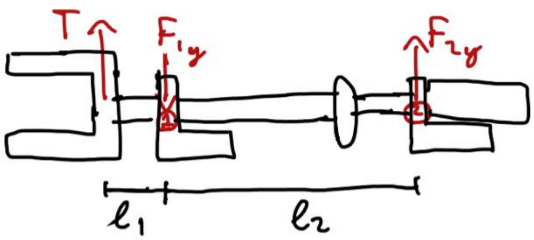
$\therefore \tau_i = \frac{0.4}{1.6} = \boxed{0.25\,Nm}$ per motor

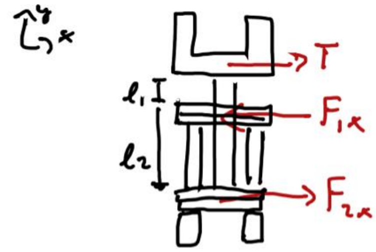
$\therefore$ Match 0.25Nm to $\frac{1}{2}\tau_{stall}$ of LDO

$\Rightarrow \boxed{57:1\ \text{LDO}}$

Appendix C

Power lost through friction of bearings





$$\Sigma F_y = 0 = T - F_{1y} + F_{2y}$$

$$\Sigma M_1 = 0 = -T\ell_1 + F_2\ell_2 \Rightarrow \boxed{F_{2y} = \frac{T\ell_1}{\ell_2}} \quad \therefore F_{1y} = T + F_{2y} = \boxed{T\left(1 + \frac{\ell_1}{\ell_2}\right)}$$

$$\therefore F_x = F_y$$

$\therefore$ frictional power loss $= \tau\omega$

$$\tau = \mu R_{shaft}\sqrt{F_x^2 + F_y^2} \quad \text{for each bushing}$$

$$= \mu R_{shaft}\sqrt{2}F \quad \text{for each bushing}$$

$$\therefore \boxed{\begin{array}{l} ① \; P = 3 \cdot \mu R_{shaft}\sqrt{2}F_1 \cdot \omega \\ ② \; P = 2 \cdot \mu R_{shaft}\sqrt{2}F_2 \cdot \omega \end{array}}$$

Power losses from bushing friction

μ between nylon & aluminium = 0.06

R_{shaft} = 5/32" = 0.004m

ω = 2.213 rad/s

ℓ_1 = 1" = 0.0254m

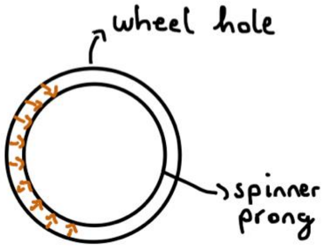
ℓ_2 = 4" = 0.1016m

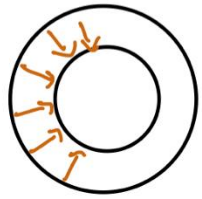
$\Rightarrow F_1 = 0.5N$; $F_2 = 0.1N$

$P_{total} = P_1 + P_2 = \boxed{0.00128W}$

$\therefore$ Very little power lost from friction on bushing

Appendix D





∴ Friction between spinner and hole increases when the prong diameter is smaller.

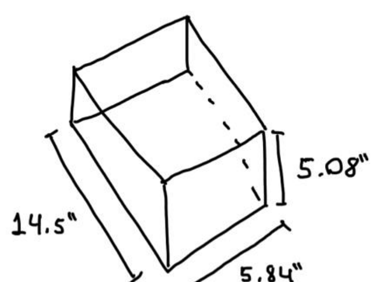
∴ $\boxed{\phi = 1''}$

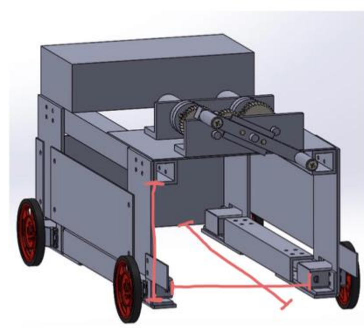
↳ Just under ϕ of the wheel hole.

Appendix E

Ball $\phi \simeq 2.8''$

∴ Ball Volume $\simeq 11.3''^3 \Rightarrow$ 18 balls vol. $\simeq 203''^3$





Total Inner Volume $\simeq 430''^3 > 203''^3$

∴ All 18 balls released will fit

Square Area of Ball = $2.8'' \cdot 2.8'' = 7.84''^2$

∴ $\frac{14.5 \cdot 5.84}{7.84} = 10.8 \simeq 10$ balls fit without stacking

∴ Balls will stack in two rows $\Rightarrow$ total height = $2\phi = 5.6''$ MAX

However, second row of balls will sit in pockets between first row balls, and will still be secured even if half of the height is secured.

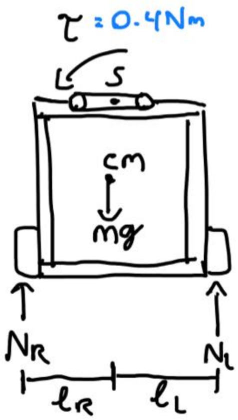
[∴ Set up a shield in front of robot of $h = 3''$ to completely prevent balls from spilling out (~2" between shield and top)

∴ Balls will enter from the top in space between spinner & counterweight.]

Appendix F

Front

$\uparrow y$



$$\Sigma F_y = 0 = N_R + N_L - mg$$

$$\Sigma M_{cm} = 0 = -l_R N_R + l_L N_L + \tau$$

$$\Rightarrow \tau = l_R N_R - l_L N_L$$

$$\therefore N_R = mg - N_L$$

$$\Rightarrow \tau = l_R mg - l_R N_L - l_L N_L$$

$$\Rightarrow \boxed{N_L = \frac{l_R mg - \tau}{l_R + l_L}}$$

$$\Rightarrow \boxed{N_R = mg + \frac{\tau - l_R mg}{l_R + l_L}}$$

for balance when driving

$$\therefore l_R = l_L \Rightarrow \boxed{\begin{aligned} N_L &= \frac{mg}{2} - \frac{\tau}{2l} \\ N_R &= \frac{mg}{2} + \frac{\tau}{2l} \end{aligned}}$$